END
DATE
FILMED
9-80
DTIC

1.0

2.8 2.5

3.2 2.2

3.6

4.0 2.0

1.1

1.8

1.25 1.4 1.6

MICROCOPY RESOLUTION TEST CHART

THE
GEORGE
WASHINGTON
UNIVERSITY

A ⑫ LEVEL II

STUDENTS FACULTY STUDY R
ESEARCH DEVELOPMENT FUT
URE CAREER CREATIVITY CC
MMUNITY LEADERSHIP TECH
NOLOGY FRONTIE SIGN
ENGINEERING APP ENC
GEORGE WASHIN NIV

DTIC
S ELECTE D
AUG 2 2 1980

B

SCHOOL OF ENGINEERING
AND APPLIED SCIENCE

80 8 22 030

(12) **LEVEL** II

(6) DEVELOPMENT OF FRACTURE
MECHANICS CONCEPTS APPLICABLE
TO AIRCRAFT STRUCTURES.

(10) P. K. Poulose ▰ D. L. Jones

(9) Final Scientific Report, 1 *may* 78 - 3φ *µ* 7

Sponsored by

Naval Air Systems Command

Contract No. N 00019-78-C-0301
(15)

Approved for Public Release

Distribution Unlimited

May 1, 1978 - April 30, 1979

(11) **MAY ∎79**   (12) 27

School of Engineering and Applied Science

The George Washington University

Washington, D. C. 20052

**DTIC
S ELECTE D
AUG 2 2 1980
B**

ABSTRACT

The dependence of cyclic nonlinear energy toughness on the fatigue lives of precracked specimens was studied using two aluminum alloys, 2024-T3 and 7075-T6. An exponentially increasing load program was used for determining the fatigue lives. The cyclic toughness values for both alloys decreased as a logarithmic function of the fatigue lives. For a given life the toughness value for 2024-T3 was higher than that for 7075-T6, but the difference decreased with increasing cyclic life.

An accelerated test program for prediction of constant amplitude fatigue lives of precracked specimens was undertaken. An analytical basis for this method was developed using an exponentially increasing load sequence. Accelerated tests were carried out on 2024-T3 and 7075-T6 using linearly and exponentially increasing loads and appropriate curves of the form of higher-order hyperbolas were fitted to the data using the method of least squares. The constant amplitude curve predicted from these results will be compared with the constant amplitude test results in the second stage of this program.

INTRODUCTION

In high toughness materials large amounts of plasticity and subcritical crack growth precede unstable fracture, and hence, the linear fracture mechanics toughness criterion is not appropriate. The nonlinear energy fracture toughness, $\tilde{G}_c$, has been proposed as a criterion for fracture that can be used for large thickness ranges [1,2], and its consistency has been verified by a considerable number of experiments [3,4,5].

The feasibility of applying the nonlinear energy fracture toughness criterion to the cyclic loading of precracked specimens was considered, since a fracture toughness criterion should be more appropriate than the conventional S-N curve representation normally used for smooth specimens. Under the Naval Air Systems Command Contract N00019-77-C-0160, fatigue tests were performed by applying an incrementally increasing load program to a number of center-cracked 2024-T3 and 7075-T6 aluminum specimens and the cyclic nonlinear energy values, $\tilde{G}_{fc}$, were determined as a function of the number of cycles to failure. These curves assumed the appearance of compressed S-N curves, which is reasonable since the crack initiation phase was essentially eliminated because of the use of precracked specimens.

The exponentially increasing load amplitude program employed in this research program represents one type of accelerated fatigue test. The common feature of all accelerated tests is that a cyclic load function whose amplitude increases with time is applied to the

specimen. Such a test in which the load amplitude is increased
linearly with the cycle number was used by Prot [6] to predict the
constant amplitude fatigue limits of unnotched specimens in com-
pletely reversed cyclic loading (R=-1). Similar accelerated tests
were later used by several investigators to predict with reasonable
accuracy the endurance limit. Recently Basavaraju and Lim [7] de-
veloped an analytical method to determine the entire S-N curve from
accelerated test results using a linearly increasing load amplitude.
It was assumed that Miner's cumulative damage rule was applicable
in accelerated testing. Miner's rule is generally considered to be
more appropriate in the crack growth phase than in the crack initi-
ation phase. Hence, this method appears to be suitable for applica-
tion to fatigue failures of materials containing cracks.

A research program was initiated under the Naval Air Systems
Command Contract N00019-78-C-0301 to examine the feasibility of
using accelerated test results for determination of constant
amplitude fatigue lives of materials containing flaws. This in-
volved the development of an analytical basis as well as experi-
mental verification of the method. Since the program was designed
for materials containing cracks, a stress intensity, K, approach
rather than a stress approach was adopted. However, since all the
tests in the initial stage were planned on one specimen geometry
and size, the analysis was based on the stress approach, which
would later be modified to account for the geometry effects using
the stress intensity approach.

In this report nonlinear cyclic energy toughness test results on 2024 and 7075 aluminum alloys comprising the entire range of cyclic lives is presented. The analytical basis for the accelerated fatigue test program where the load increases exponentially with cycle number has been developed. Accelerated test data on two alloys 2024-T3 and 7075-T6 have been obtained and appropriate constants for the hyperbolas that fit these data points have been determined.

DETERMINATION OF THE CYCLIC NONLINEAR
ENERGY FRACTURE TOUGHNESS

The cyclic nonlinear energy fracture toughness, $\tilde{G}_{fc}$, values were determined on 2024-T3 and 7075-T6 specimens of length 30 in. and width 12 in. and crack length-to-width ratio of 0.5. The load was increased exponentially with the cycle number according to the relation

$$F_n = F_0(1-e^{-nx}) \;,$$

where F_0 = fracture load in monotonic loading

   n = cycle number

   x = increment per cycle, and

   F_n = the load corresponding to cycle number n.

Details of the test program and a preliminary discussion of the test results were given in the Final Scientific Report for 1978. Further discussion of the test results with the help of graphic illustrations of the test results in the entire range of tests is presented in this report.

The variation of $\tilde{G}_{fc}$ as a function of the number of cycles to failure, N, for 2024-T3 and 7075-T6 aluminum alloys is seen in Figs. 1 and 2, respectively. For both alloys the values of $\tilde{G}_{fc}$ exhibited a tendency to decrease with increasing cyclic life. The decrease was greater in 2024 than in 7075, but at any given cyclic life, $\tilde{G}_{fc}$ was higher for 2024 than 7075, reflecting the higher toughness of 2024-T3. On semilog plots these data appear

as bilinear curves with a small nearly horizontal region at the
low cyclic life range and a second large region with a sleeper
slope. These curves did not exhibit a tendency for the load to
level off in the higher cyclic life range indicating that the
threshold values of $\tilde{G}_{fc}$ for both materials are very low.

ACCELERATED FATIGUE TEST FOR DETERMINATION
OF CONSTANT AMPLITUDE FATIGUE LIVES

Analytical Development

The analytical method developed by Basavaraju and Lim [7] was used for smooth specimens under completely reversed cyclic loading (R=-1). However, the method should be applicable to any R value as long as the R used for the accelerated test is appropriate to the R value for the constant amplitude tests. Since it has been widely demonstrated that negative and small positive R values do not alter the fatigue crack growth rates, accelerated test data at R = 0.1 used in this test program should be applicable to a wide range of constant amplitude test conditions. Other factors affecting the fatigue crack growth rates, such as the environment, loading rate, etc., should also be examined carefully to make certain that the accelerated test conditions are appropriate to the conditions for which the predicted response is desired. In addition, the results of the accelerated testing program may be applicable to variable amplitude fatigue loadings such as those experienced by aircraft structures. The applicability of this method would be dependent upon the accuracy of a cumulative damage law, such as Miner's rule, to the load spectra experienced by the structures.

In the present research program the analytical basis has been developed for an exponentially increasing load program, in which the cyclic stress amplitudes increased according to the relation

$$S_r = S_u(1 - e^{-an}) , \qquad\qquad (1)$$

where n = cycle number,

    a = constant,

    S_u = gross ultimate fracture strength in uniaxial loading, and

    S_n = gross fracture strength at cycle number n.

In this development, the following assumptions were made:

(1) The relation between the constant stress amplitude, S, and the number of cycles to failure, N, for precracked specimens is a hyperbola asymptotic to the endurance limit, S_e.

(2) Under an exponentially increasing stress amplitude, the relation between S_f and N_d is also a hyperbola asymptotic to the fatigue limit, where S_f is the accelerated fatigue fracture strength and N_d is the number of cycles above the fatigue limit.

(3) The stress history below the endurance limit causes no structural damage.

(4) Miner's cumulative damage rule is applicable to both constant amplitude and accelerated tests. It is recognized that these hyperbolas may be of a higher order.

As in the case of unnotched specimens, the expression for constant amplitude test data may be given as

$$(S - S_e)^m \, N = C \, , \tag{2}$$

in which m and C are constants. The accelerated test results also can be represented as a higher-order hyperbola as

$$(S_f - S_e)^\gamma \, N_d = D \, , \tag{3}$$

in which γ and D are constants. Equating Eq. (1) at final fracture and at the endurance limit yields

$$S_f = S_u(1 - e^{-an_f}) \, , \tag{4}$$

where n_f is the number of cycles to failure and

$$S_e = S_u(1 - e^{-an_0}) \, , \tag{5}$$

where n_0 is the number of cycles during which no damage occurs. From Eqs. (4) and (5), it is seen that

$$\frac{S_u - S_e}{S_u - S_f} = \frac{e^{an_f}}{e^{an_0}} = e^{a(n_f - n_0)} = e^{aN_d} \, , \tag{6}$$

since $N_d \equiv n_f - n_0$. Solving Eq. (6) for N_d gives

$$N_d = \ln \left(\frac{S_u - S_e}{S_u - S_f} \right) 1/a = \frac{1}{a} \ln \left(\frac{S_u - S_e}{S_u - S_f} \right) \, . \tag{7}$$

Combining Eqs. (3) and (7) yields

$$(S_f - S_e)^\gamma \ln \left(\frac{S_u - S_e}{S_u - S_f} \right) = aD \, . \tag{8}$$

Therefore,

$$S_f = S_e + \left[\frac{Da}{\ln(\frac{S_u - S_e}{S_u - S_f})} \right]^{1/\gamma}$$

$$= S_e + D^p \left[\frac{a}{\ln(\frac{S_u - S_e}{S_u - S_f})} \right]^p \tag{9}$$

where $p = 1/\gamma$.

The S-N curve, Eq. (2), can be rewritten in the form

$$N = (\frac{C}{S - S_e})^m .$$

In accelerated testing only one cycle is normally applied at each stress level. Hence, Miner's rule can be written as

$$\sum_{j=1}^{d} \frac{1}{N_j} = \frac{1}{N_1} + \frac{1}{N_2} \cdots + \frac{1}{N_j} \cdots \frac{1}{N_d} = 1 , \tag{10}$$

where

$$N_j = (\frac{C}{S_j - S_e})^m , \tag{11}$$

and

$$S_j = S_u [1 - e^{-a(n_0+j)}] . \tag{12}$$

Eqs. (5, 11 and 12) can be combined to give

$$\frac{1}{N_j} = \frac{S_u^m}{C} [e^{-an_0} - e^{-a(n_0+j)}]^m$$

$$= \frac{(S_u - S_e)^m}{C} (1-e^{-aj})^m . \tag{13}$$

Making use of Eqs. (11-13) permits Eq. (10) to be written as

$$\sum_{j=1}^{d} \frac{1}{N_j} = \frac{(S_u - S_e)^m}{Ca} \sum_{j=1}^{d} (1-e^{-aj})^m$$

$$= \frac{(S_u - S_e)^m}{Ca} \cdot P = 1 . \tag{14}$$

An approximate closed-form expression for Eq. (14) can be obtained by integration and evaluation of the constants as

$$\sum_{j=1}^{d} \frac{1}{N_j} = \frac{(S_u - S_e)^m}{Ca} [aN_d + m e^{-aN_d} - \frac{m(m-1)}{4} e^{-2aN_d}$$

$$+ \frac{m(m-1)(m-2)}{18} e^{-3aN_d} - \frac{m(m-1)(m-2)(m-3)}{96} e^{-4aN_d}$$

$$- 1.4718m + 0.6317m^2 - 0.1884m^3 + 0.03052m^4 - 0.002011m^5]$$

$$= \frac{(S_u - S_e)^m}{Ca} \cdot Q = 1 . \tag{15}$$

A comparison of the actual sum P and the approximate sum Q in the appropriate range of N_d values for different exponential increments, a, is given in Table 1. The agreement between P and Q is within five percent in all cases and within 2.5 percent in most cases.

From two test results where the exponential increments are a_1 and a_2 and the numbers of cycles causing damage are N_{d_1} and N_{d_2}, it can be seen that

$$\frac{a_2 \ Q_1}{a_1 \ Q_2} = 1 \ . \tag{16}$$

Then m can be obtained from Eq. (16) by the use of numerical techniques. Since S_u, S_e and m are constants, C can be evaluated from Eq. (15). Thus, the complete S-N curve is obtained. The constants S_e, γ, and D are obtained from the accelerated test data.

Experimental Results

At present, constant amplitude fatigue life data on precracked specimens are scarce, since most fatigue research has emphasized fatigue crack growth rate studies. Only a limited amount of fatigue life data has been generated on 7075-T6 and 2024-T3 aluminum alloys from fatigue crack growth results [8]. Hence, it was necessary to generate data for both constant amplitude and accelerated tests.

Accelerated tests, in which the stress amplitude was increased exponentially according to relation (1), were performed on 2024-T3 and 7075-T6 center-cracked specimens. The specimen geometry and test procedure were essentially the same as that used for determination of the nonlinear energy fracture toughness as described in prior progress reports.

The peak load versus the number of cycles to failure plots for the accelerated tests on 2024-T3 and 7075-T6 are shown in Figs. 3 and 4, respectively. Curve fitting techniques were used to obtain curves in the form of expression (8). The constants for 2024-T3 are: $S_e = 1.34$ ksi, $\gamma = 7.0$ and $D = 6.0 \times 10^8$ and $S_e = 0.81$ ksi, $\gamma = 7.1$ and $D = 6.6 \times 10^8$ for 7075-T6. A better correlation between the experimental data and the curves will be desirable, for which additional computer runs are planned.

As an additional means of exploring the use of accelerated tests for determining constant amplitude lives, a series of tests was performed using a linearly increasing load program. The

geometry of these specimens was the same as that used for the exponentially increasing load program. In this case also the curves were expected to fit Eq. (3), when appropriate constants are used. Since linear load increments were used

$$N_d = \frac{S_f - S_e}{\overset{\circ}{S}} ,$$ (17)

where $\overset{\circ}{S}$ is the load increment per cycle. Therefore,

$$(S_f - S_e)^{\gamma+1} = D\overset{\circ}{S}$$ (18)

or

$$S_f = S_e + S_s(\overset{\circ}{S})^p ,$$ (19)

in which S_e, S_s and p are constants. Since Eq. (19) is in a more convenient form than Eq. (3), it was used for determination of the constants for the curve. For the 2024-T3 alloy, the constants were obtained as S_e = 0.134 ksi, S_s = 13.8 and p = 0.11. The experimental data and the corresponding curve are shown in Fig. 5, which shows quite good correlation in the range tested.

SUMMARY

Under this research program cyclic, nonlinear energy, fracture toughness values, $\tilde{G}_{fc}$, were determined for 2024-T3 and 7075-T6 aluminum alloys. The toughness values for both alloys were found to decrease as logarithmic functions of the number of cycles to failure. The $\tilde{G}_{fc}$ toughness values for 2024-T3 were higher than the corresponding values (at the same cyclic life) for 7075-T6 over the entire range of cyclic lives obtained in this program.

An analytical basis has been developed for prediction of constant amplitude fatigue lives of precracked specimens from accelerated tests, using exponentially increasing loads. Accelerated test data for exponentially increasing loads in 2024-T3 and 7075-T6 center-cracked sheets and for linearly increasing loads in 2024-T3 sheets were obtained. Certain higher-order hyperbolas were fitted to these experimental results by use of the method of least squares to optimize the constants included in the analytical expressions. For the exponentially varying test results, the analytical curve fit the data reasonably well while the fit was quite good for the linearly varying load programs. These studies show that the approach of employing accelerated test data to predict the constant amplitude test results for specimens containing cracks is feasible. The ability to make such predictions is clearly of significant importance to all structures subjected to a large number of fatigue cycles.

REFERENCES

1. J. Eftis, and H. Liebowitz, On Fracture Toughness Evaluation for Semibrittle Fracture. Engrg. Fract. Mech., 1975, Vol. 7, pp. 101-136.

2. J. Eftis, D. L. Jones and H. Liebowitz, On Fracture Toughness in the Nonlinear Range. Engrg. Fract. Mech., 1975, Vol. 7, pp. 491-504.

3. H. Liebowitz, D. L. Jones and P. K. Poulose. Development of the Nonlinear Energy Method for Determination of Fracture Toughness Values. Prospects of Fracture Mechanics, ed. by Sih, Van Elst and Broek, Noordhoff, 1974, pp. 103-123.

4. D. L. Jones, P. K. Poulose and H. Liebowitz. A Comparison of the Effect of Specimens Thickness and Subcritical Crack Growth on Several Nonlinear Fracture Toughness Parameters. Proc. Sec. Int'l. Conf. on Mechanical Behavior of Materials, Boston, 1976, pp. 1252-1257.

5. D. L. Jones, P. K. Poulose, J. Eftis and H. Liebowitz. $\tilde{G}_c$ and R Curve Fracture Toughness Values for Aluminum Alloys under Plane Stress Conditions. Engrg. Fract. Mech., 1978, Vol. 10, pp. 433-452.

6. E. M. Prot. Fatigue Testing under Progressive Loading, A New Technique for Testing Materials. Revue de Metallurgue, 1948, Vol. 45, pp. 481-489. Translated by E. J. Ward, WADC-TR-52-148, AD-2176, 1952.

7. C. Basavaraju and C. K. Lim. An Analytical Approach to Determine Conventional S-N Curves from Accelerated Fatigue Data, Experimental Mechanics, 1977, pp. 375-380.

8. A. J. McEvily and T. L. Johnston. Proceedings of the International Conference on Fracture, Sendai, Japan, 1965, pp. 515-546.

Table 1. Comparison of actual values (P) in summation using Miner's Rule with those from the approximate expression (Q).

				m			
	1.	1.5	2	2.5	3	3.5	4
a = 0.2, N = 20							
P	15.57	14.22	13.17	12.30	11.58	10.96	10.41
Q	15.09	13.72	12.68	11.83	11.11	10.48	9.94
% Error	3.1	3.5	3.7	3.8	4.1	4.3	4.5
a = 0.1, N = 30							
P	20.97	18.40	15.44	14.86	13.55	12.45	11.49
Q	20.50	17.91	15.98	14.43	13.12	12.02	11.08
% Error	2.2	2.7	2.8	2.9	3.2	3.4	3.6
a = 0.05, N = 50							
P	32.10	27.27	23.64	20.78	18.45	16.51	14.87
Q	31.64	26.78	23.22	20.39	18.06	16.13	14.51
% Error	1.4	1.8	1.8	1.9	2.1	2.3	2.4
a = 0.02, N = 100							
P	57.20	46.36	38.45	32.40	27.63	23.77	20.59
Q	56.77	45.83	38.08	32.11	27.30	23.44	20.32
% Error	0.8	1.2	1.0	0.9	1.2	1.4	1.3
a = 0.01, N = 200							
P	113.97	92.32	76.53	64.45	54.93	47.23	40.91
Q	113.53	91.65	76.15	64.22	54.61	46.87	40.63
% Error	0.4	0.7	0.5	0.4	0.6	0.8	0.7

		m					
	1	1.5	2	2.5	3	3.5	4

a = 0.002, N = 500

	1	1.5	2	2.5	3	3.5	4
P	184.26	122.71	84.25	59.08	42.08	30.33	22.07
Q	183.94	121.16	84.05	59.47	41.97	29.96	22.01
% Error	0.2	1.3	0.3	0.7	0.3	1.2	0.3

a = 0.001, N = 1000

	1	1.5	2	2.5	3	3.5	4
P	368.20	245.16	168.29	117.99	84.02	60.57	44.06
Q	367.88	242.32	168.09	118.94	83.93	59.92	44.02
% Error	0.1	1.2	0.1	0.8	0.1	1.1	0.1

a = 0.0005, N = 2000

	1	1.5	2	2.5	3	3.5	4
P	736.08	490.07	336.38	235.82	167.92	121.01	88.05
Q	735.76	484.63	336.18	237.88	167.86	119.84	88.03
% Error	0.0	1.1	0.1	0.9	0.0	1.0	0.0

a = 0.00025, N = 3000

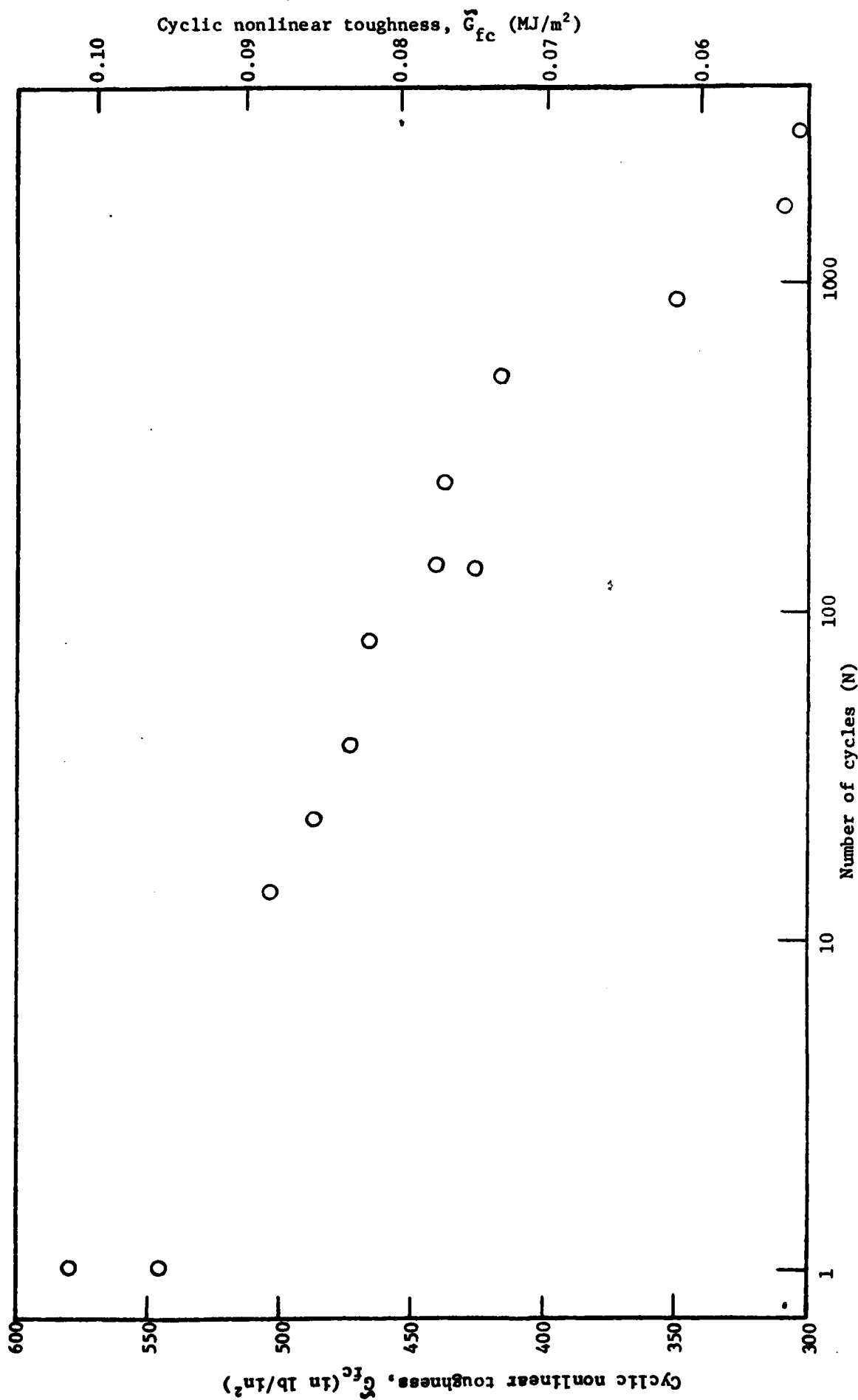|	1	1.5	2	2.5	3	3.5	4
P	889.73	535.31	332.81	211.67	136.89	89.68	59.35
Q	889.47	524.97	332.67	215.80	136.95	87.89	59.44
% Error	0.0	2.0	0.0	2.0	0.0	2.0	0.2

Fig. 1. Variation of cyclic nonlinear energy toughness with number of load cycles to failure in 2024-T3.

Cyclic nonlinear energy toughness, $\hat{G}_{Ec}$ (MJ/m^2)

Number of cycles (N)

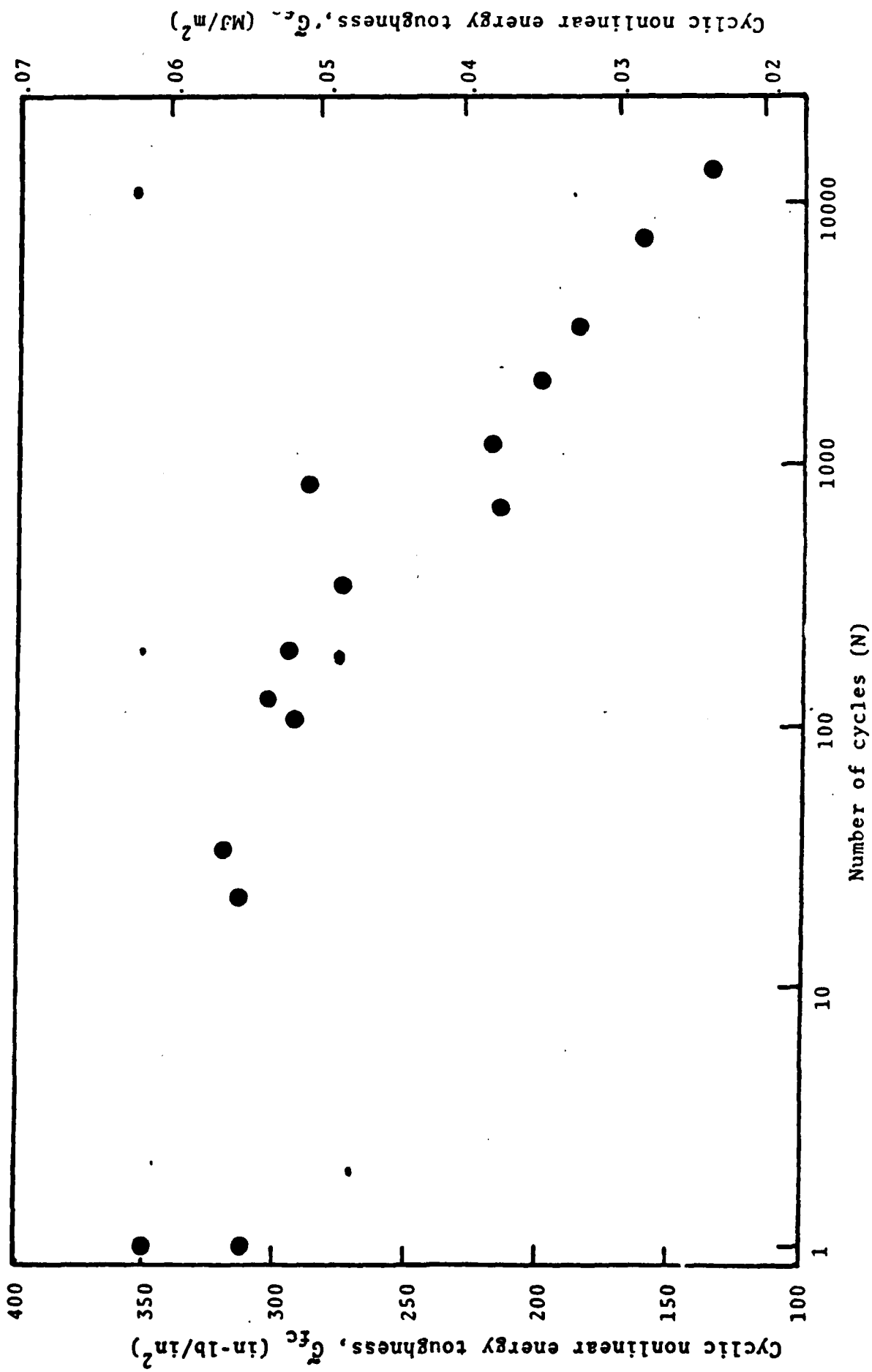Cyclic nonlinear energy toughness, $\hat{G}_{Ec}$ (in-lb/in^2)

Fig. 2. Variation of cyclic nonlinear energy toughness with number of load cycles to failure in 7075-T6 alloy.

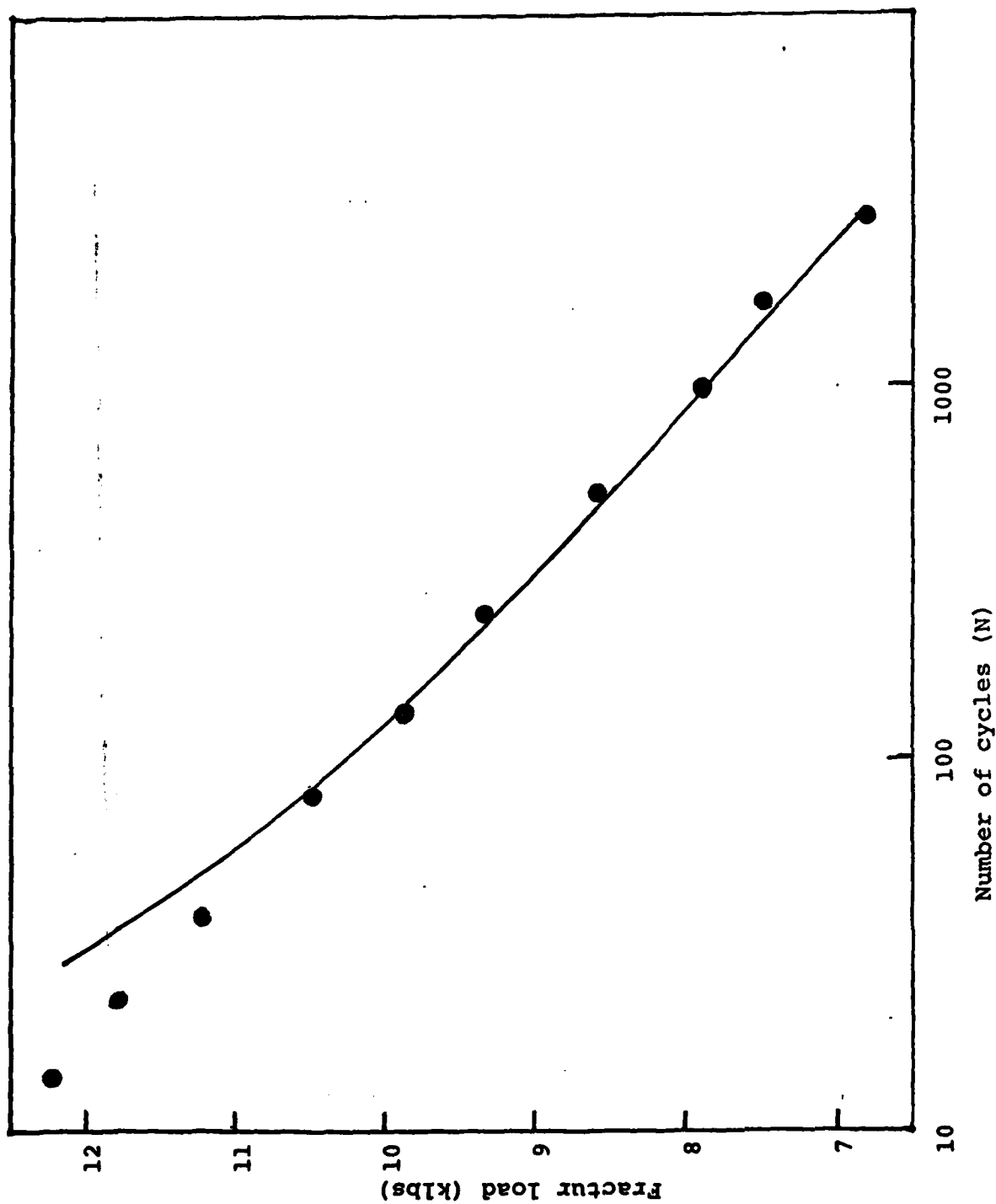Fig. 3. Variation of fracture load with number of load cycles to failure in 2024-T3 using exponentially increasing load program.
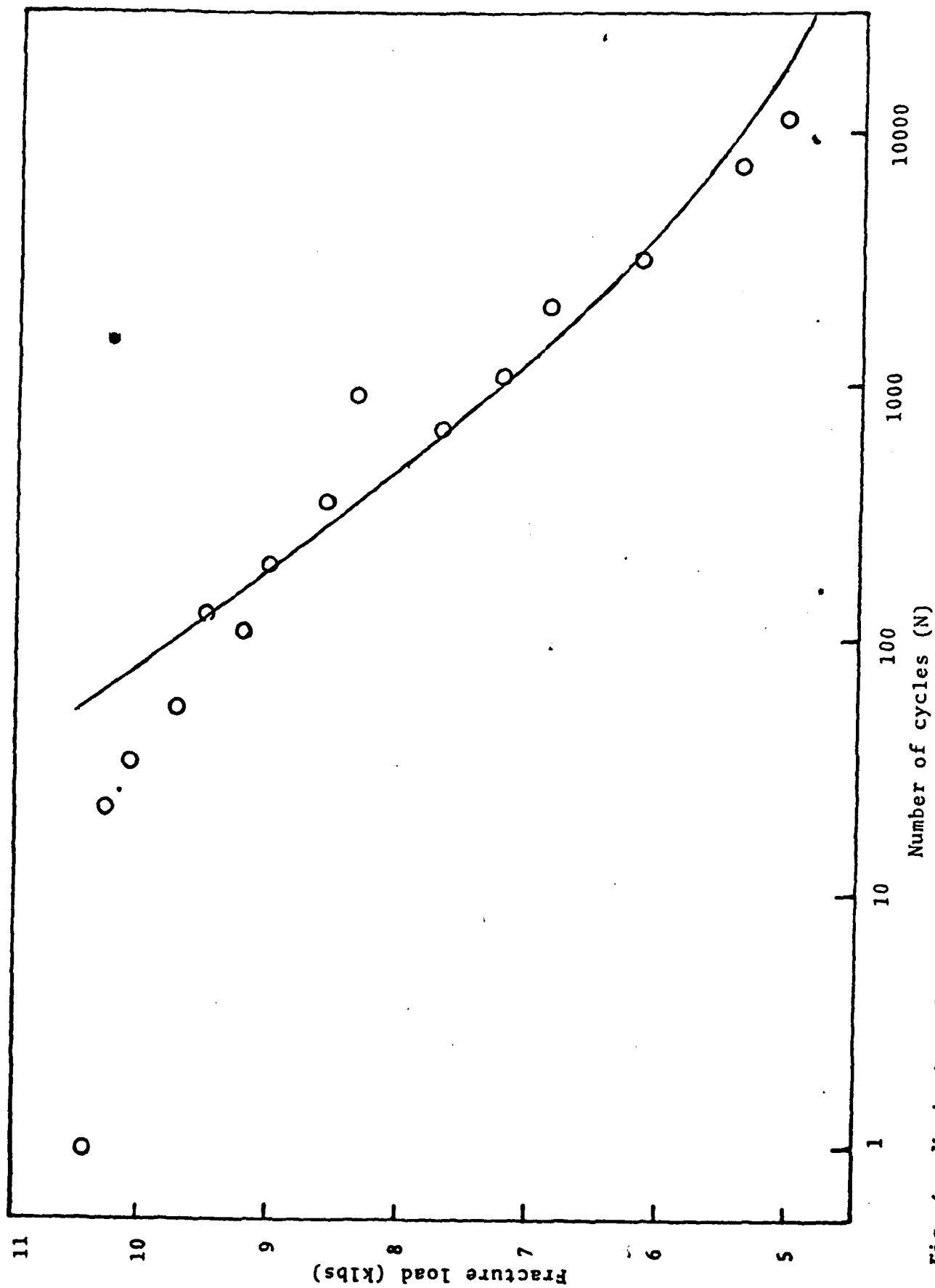
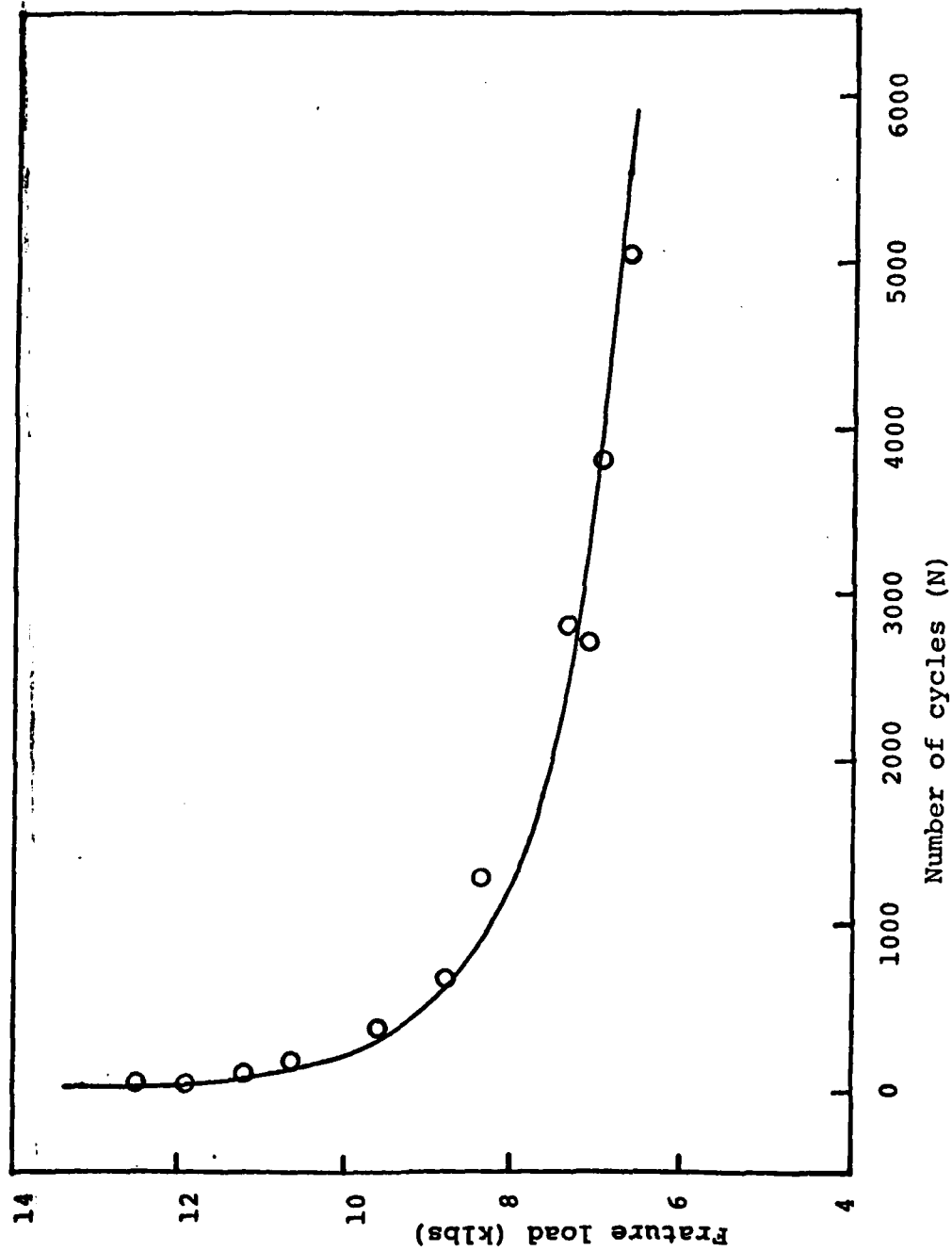Fig. 4.   Variation of fracture load with number of load cycles to failure in 7075-T6 alloy.

Fig. 5. Variation of fracture load with number of load cycles to failure in 2024-T3 using linearly increasing load program.

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A018 233	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DEVELOPMENT OF FRACTURE MECHANICS CONCEPTS APPLICABLE TO AIRCRAFT STRUCTURES		5. TYPE OF REPORT & PERIOD COVERED Final Scientific Report May 1, 1978-April 30, 1979
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) P. K. Poulose and D. L. Jones		8. CONTRACT OR GRANT NUMBER(s) NAVY N00019-78-C-0301
9. PERFORMING ORGANIZATION NAME AND ADDRESS School of Engineering and Applied Science, The George Washington University, Washington, D.C. 20052		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS NAVAL AIR SYSTEMS COMMAND, Department of the Navy, Washington, D.C. 20361		12. REPORT DATE May 1979
		13. NUMBER OF PAGES 25
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Fracture	Accelerated test
Nonlinear toughness	Constant amplitude life
Fatigue	Stress intensity
Aluminum alloys	Miner's rule

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The dependence of cyclic nonlinear energy toughness on the fatigue lives of precracked specimens was studied using two aluminum alloys, 2024-T3 and 7075-T6. An exponentially increasing load program was used for determining the fatigue lives. The cyclic toughness values for both alloys decreased as a logarithmic function of the fatigue lives. For a given life the toughness value for 2024-T3 was higher than that for 7075-T6, but the difference decreased with increasing cyclic life.
(Continued on other side)

An accelerated test program for prediction of constant amplitude
fatigue lives of precracked specimens was undertaken. An analytical
basis for this method was developed using an exponentially increasing
load sequence. Accelerated tests were carried out on 2024-T3 and 7075-T6
using linearly and exponentially increasing loads and appropriate curves
of the form of higher-order hyperbolas were fitted to the data using the
method of least squares. The constant amplitude curve predicted from
these results will be compared with the constant amplitude test results
in the second stage of this program.